ULTRASONIC WAVE PROPAGATION THROUGH AN INTERFACE WITH A STEP DISCONTINUITY

A. Minachi and R.B. Thompson

Center for Nondestructive Evaluation
Iowa State University
Ames, Iowa 50011

M.S. Good and A.A. Diaz

Pacific Northwest Laboratories
Operated by Battelle Memorial Institute
Richland, WA 99352

INTRODUCTION

The condition of an interface through which an ultrasonic wave passes as it enters a material is an important factor in ultrasonic nondestructive evaluation. Most modeling studies of ultrasonic inspection assume that this interface is smooth. However, in real life this may not be the case. In the case of nuclear reactor components, factors such as weld overlay, claddings, grinding and diametrical shrink can give part surfaces a wavy, corrugated or abruptly stepped topography. M. S. Good [1] has provided some estimate of what surface conditions exist in nuclear reactor components, with some examples being illustrated in Fig. 1. These irregular surfaces can severely distort or redirect the ultrasonic beam, leading to false indications of size and location of defects.

The object of this study is to develop a model to predict the distortion of ultrasonic beams passing through rough, irregular interfaces. Such a model could be used to investigate the inspectability of particular components, e.g. to decide if a rough surface needs more smoothing for an accurate ultrasonic inspection. In this paper, the physical assumptions underlying the model are reviewed. The results of preliminary validation tests are reported. In those tests, the model is evaluated for a few test cases involving a step discontinuity and those results are compared to experiment.

THEORETICAL BACKGROUND

General Overview of the Model

The model utilizes a hybrid technique, which separately considers three stages for propagation of the ultrasonic beam through a rough interface. From the transducer to the rough surface, the propagation phenomena, within the Fresnel approximation, is fully included based on the Gauss-Hermite beam model. From the interface to an imaginary transmitted plane in the immediate vicinity of the interface, a ray tracing technique is used to account for the aberrations induced on the beam in that vicinity. In this region, the effects of beam spread due to diffraction are neglected. From the transmitted plane and beyond, the Gauss-Hermite model is again applied.

Gauss-Hermite Beam Model

The Gauss-Hermite beam model which has been developed over the past several years can be used to describe ultrasonic beam propagation in fluids [2] and isotropic [3] and anisotropic solid media [4-6]. In this Gauss-Hermite model, the beam is represented as a superposition of bound basis functions, each of which spreads during propagation in accordance with the principles of diffraction. The behavior of each of these basis functions is derived by representing it as an angular spectrum of plane waves and then employing the Fresnel approximation to allow the integrals over spatial frequency to be evaluated analytically. For the case of anisotropic media, certain parameters in the theory, which determine beam skew and divergence, can be directly related to the slowness surfaces. The net results is that the radiation of an ultrasonic source propagating in the z-direction can be represented as

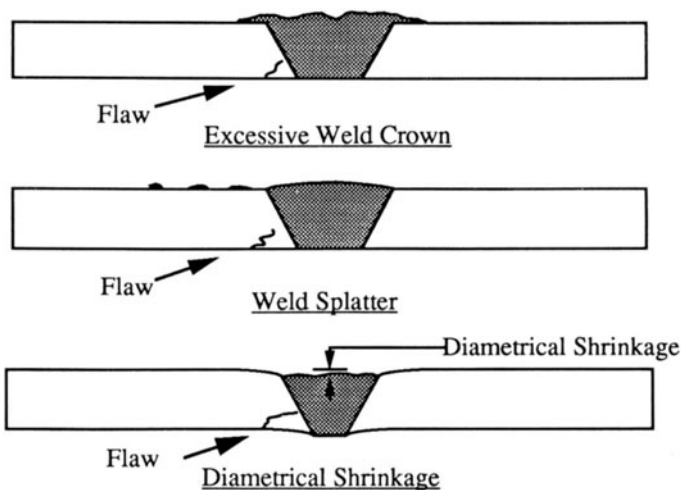

Figure 1. Irregular surface conditions in nuclear reactor components.

$$u(x,y,z) = \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} C_{mm} u_{mm}(x,y,z). \qquad (1)$$

Here the u_{mm} are the Gauss-Hermite eigenfunctions, whose transverse variations have the form of a complex Gaussian exponential multiplied by a Hermite polynomial, with amplitude, phase and width parameters depending only on the axial coordinate. The Gauss-Hermite complex constant coefficients, C_{mm}, are computed by using the orthogonality property of the Gauss-Hermite functions and knowledge of radiation pattern at the source ($z=0$). Once these coefficients are known, the displacement amplitude can be computed for any point (x,y,z). Also, by using equation (1), the normal vector to the phase front is computed by finding the gradient vector of the phase.

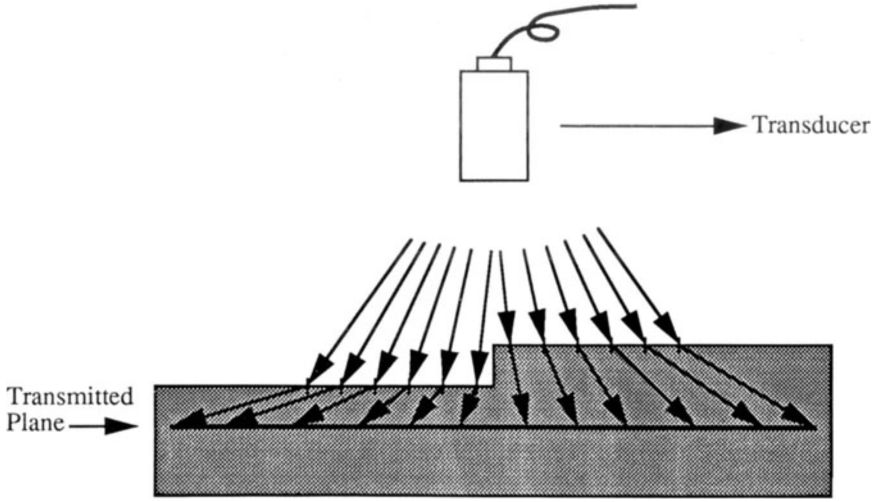

Figure 2. Schematic drawing of rays transmitting inside the sample and propagating toward transmitted plane.

Ray Tracing

A ray tracing model is used to calculate the effect of the interface on the beam, following an approach described previously [7]. As noted above, by using the Gauss-Hermite model, the vector normal to the phase front and the displacement for the incident wave are computed at each point on the interface. These normal vectors to the phase fronts define rays which pass through the interface (see Figure 2) and intersect a transmitted plane. This transmitted plane is perpendicular to the central ray and selected to lie close to the interface. To calculate the field amplitude on the transmitted plane, the rays are considered to define flux tubes, and conservation of energy is applied from the interface to the transmission plane. Thus we require

$$Z_1 \int\int_{interface\ \ plane} u_i^2(x,y)\,dA = Z_2 \int\int_{transmission\ \ plane} T^2 u_t^2(x,y)\,dA \tag{2}$$

where u_1 is the displacement of the incident wave, and u_t is the displacement amplitude on the transmission plane, T is the interface transmission coefficient, and Z is the acoustic impedance. T is assumed to have a spatial variation consistent with the angles of incidence and refraction of the involved rays.

After reconstruction of the beam pattern on the transmitted plane, new Gauss-Hermite coefficients (C_{mm}), are computed. Then the displacement at any point beyond the transmitted plane can be computed using equation (1).

Limitations of the Model

The model involves two approximations. The Fresnel approximation is inherent everywhere because of the use of the Gauss-Hermite model. This is generally not a severe limitation and has been discussed elsewhere [2-6]. In addition, use of ray tracing ignores any diffraction related beam spread between the interface and the transmitted plane. We have not fully determined the errors involved in the use of this approximation. However, we speculate that the rate of spatial variation of the surface profile should be relatively low. For very high rates of spatial variation, the ray tracing will predict excessive refraction, and the

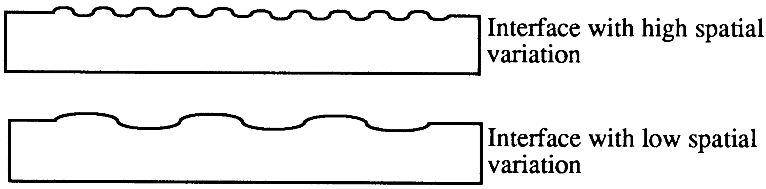

Figure 3. Surface conditions that affect the validity of the model.

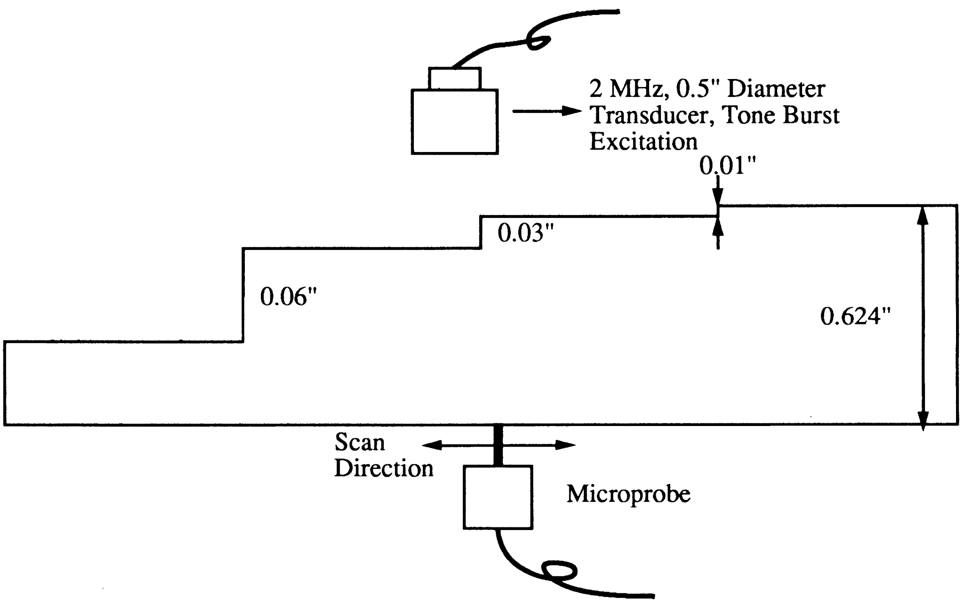

Figure 4. Experimental setup.

constructed beam on the transmitted plane becomes meaningless. Figure 3 shows an illustration of the rough surfaces with low and high rates of spatial variation. The ratio of ultrasonic wavelength to the spatial periods of interface roughness clearly should be small to use this approximation.

Another consequence of the neglect of beam spread is an error in width. Thus, the transmitted plane must be chosen as close as possible to the interface, so that ray tracing is done over as small of a distance as possible.

EXPERIMENTAL PROCEDURE

The sample used in these experiments was a stainless steel block with three different step sizes on it. The heights of the steps were 0.01, 0.03, and 0.06 inches (.025, .076 and .152 cm). The ultrasonic source used in all the experiments was a 0.5 inch, (1.27 cm) diameter planar transducer with a 2 MHz center frequency. For normal incidence, the transducer, which was excited by a tone burst, was placed 6 cm directly above each step. For oblique incidence, it was inclined at an angle such that a 45° L wave was generated in the solid and the central ray passed through the top of the step. At the bottom of the sample, a microprobe was used to receive the distorted signal passed through the step. The microprobe was scanned on a square area of 2 inch (5 cm) sides. Figure 4 shows the configuration.

The transmitted plane for normal incidence was assumed to be 0.2 cm below the top of each step. In the case of oblique incidence, the transmitted plane was inclined at an angle of 45 degrees, passing through the top of each step. In this way minimum path lengths are used. Figure 5 shows the position as the transmitted planes for each case.

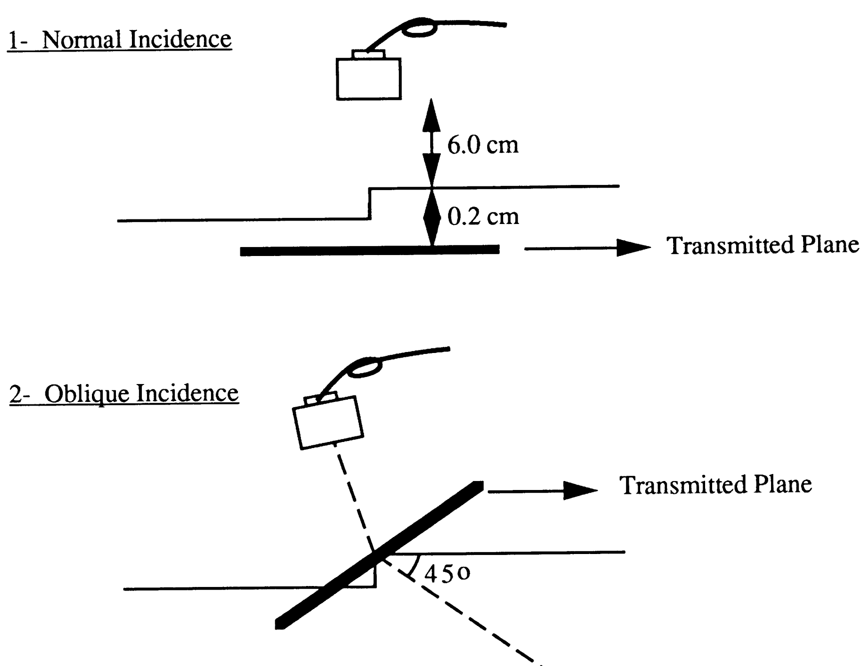

Figure 5. The position of transmitted plane in normal and oblique incidence case.

RESULTS AND DISCUSSION

Normal Incidence

In this case the transducer was placed directly above the step. Although the microprobe performed a c-scan, to compare the experimental and theoretical results, a 2-D graph of experiment and theory is presented. Figure 6 shows the comparison between theory and experiment for all the three steps.

As can be seen from the graphs, there is good agreement between experiment and theory near the center of the beam, with the theory predicting the general shape of the beam profile quite well. However, the difference between the two increases as one moves further away from the central ray. This is what was expected for two reasons. First, the model accuracy decreases away from the central ray due to the paraxial approximation used in the theory. Second, the ray tracing which does not consider the diffraction of the beam can cause errors in the beam's width. It must be noted that most of the energy is concentrated near the center

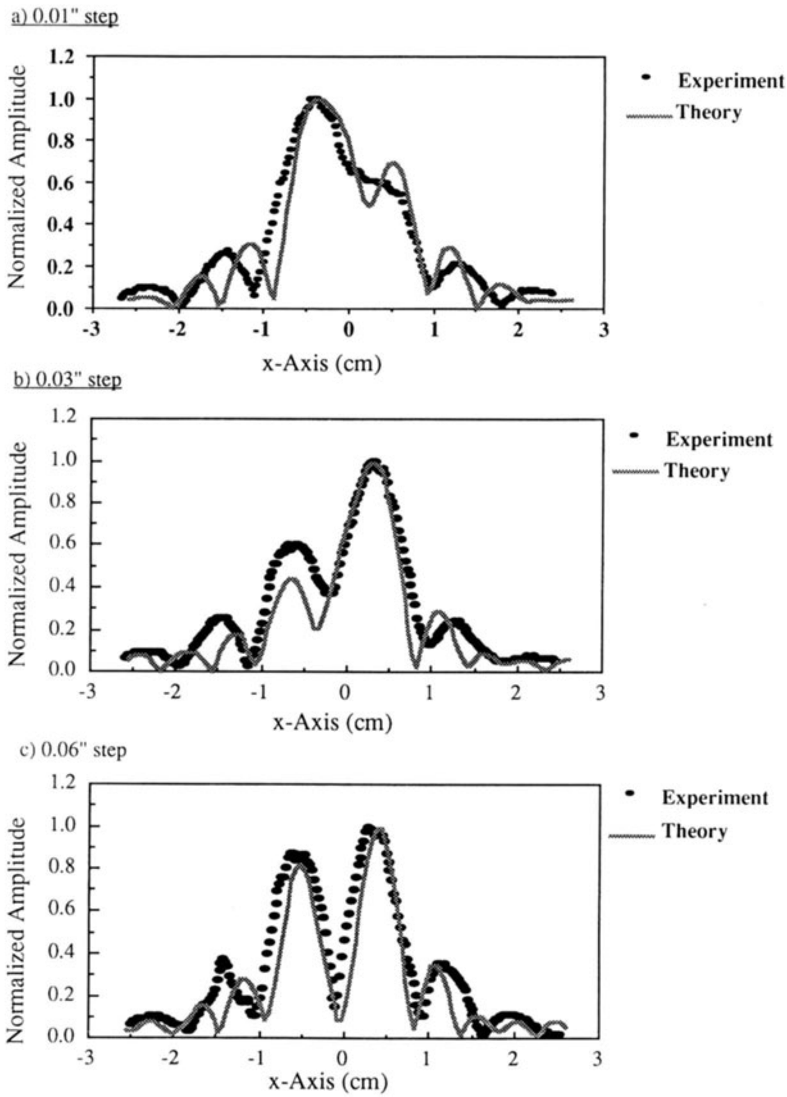

Figure 6. Comparison between experiment and theory for normal incidence.

of the beam and that this is the energy usually involved in flaw detection experiments. Errors in predictions of the side lobe structure may not affect the signal reflected from cracks or other flaws during ultrasonic inspections. The deviations between theory and experiment may also be due to errors in experimental measurements or to the fact that the transducer used in the measurements did not radiate exactly as a piston source, as assumed in the theory. These possible sources of error are being studied.

It is quite encouraging that the theory does a good job of predicting the constructive and destructive interference of the beam due to presence of steps. The size of the step and the frequency control this interference. At 0.03 inch (0.07 cm) step size, there is almost a constructive interference, but as the step size increases, it changes to a destructive interference. The possibility of such interferences must be considered in the ultrasonic examinations. As it is shown in the graphs, the inspectibility is severely reduced under certain combinations of frequency and step size.

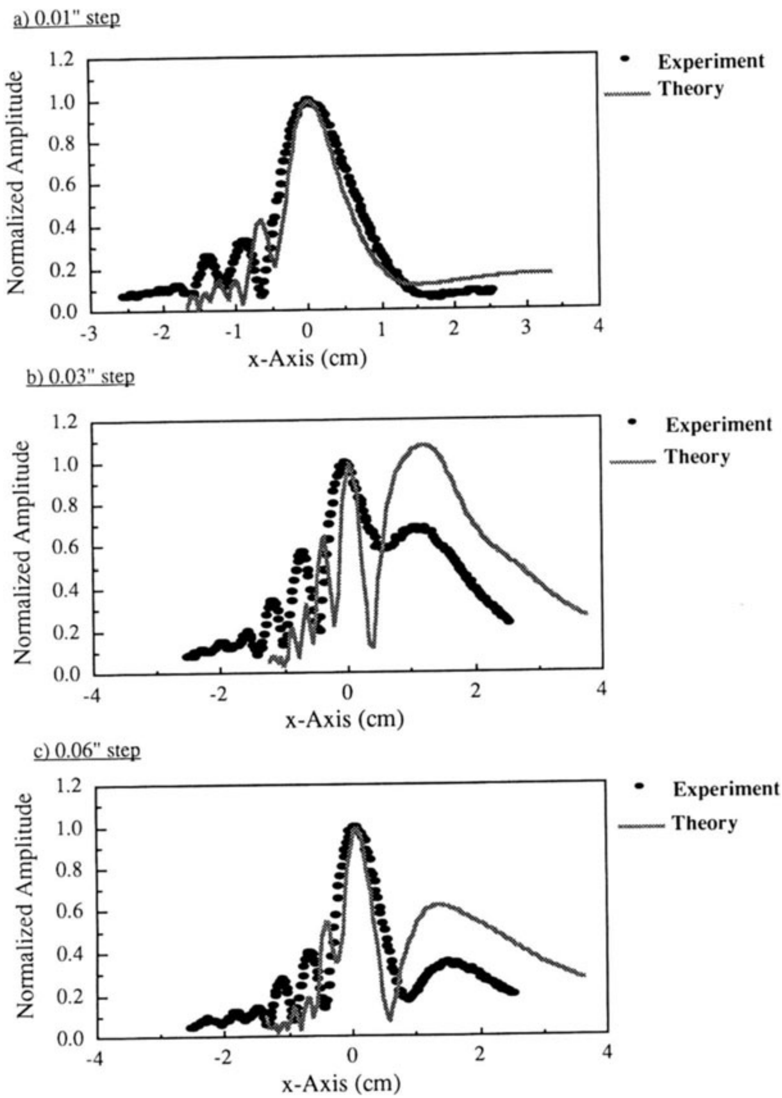

Figure 7. Comparison between experiment and theory for oblique incidence.

Oblique Incidence

The oblique incident was selected such that the transmitted wave is refracted at 45 degrees from the normal. The comparison of theory and experiment for oblique incidence are shown in Figure 7. The origin of the abscissa is relative in these plots, with the central ray passing through the lobe that is furthest to the right in each case. The results for a 0.01 inch (0.025 cm) step shows a good agreement within the main lobe, but for the other two step sizes there are considerable differences between experimental measurements and theoretical predictions. The sources of these deviations are still under study. The disagreements could have been originated from deficiencies in either the experiments or the theoretical model. Experimentally, it is much harder to adjust the transducer to a predetermined position in the oblique incidence configuration than for normal incidence, and there is the possibiity of mode converted transverse waves being detected as well as the longitudinal waves. On the theoretical side, ray tracing is more involved in the oblique incidence case than in the normal incidence case. Further studies are in process to determine whether these disagreements represent fundamental limitations on the theory or initial errors in our analytical or experimental work.

CONCLUSION

This study clearly shows the importance of the surface condition in ultrasonic inspection of materials. It also shows that, in the normal incidence case, the theoretical predictions of the beam profile closely matched the experimental data. The disagreements were mostly in side lobes and away from the central ray. This could have been caused by a) the Fresnel approximation implicit in the Gauss-Hermite model or b) the ray tracing that does not consider the beam spread near the interface.

In the oblique incidence experiments, the predictions were not in as good agreement with experiment. The results were qualitatively similar but exhibited some quantitative differences. The problems could have been due to a) the ray tracing, b) the operation of the microprobe which is primarily sensitive to the normal component of the displacement, or c) errors in experimental setup and procedures. The oblique incidence case will be studied in more detail.

ACKNOWLEDGMENTS

This work was sposored by the Electric Power Research Institute under contract RP-2687-01 and was performed at the Ames Laboratory. Ames Laboratory is operated for the U.S. Department of Energy by Iowa State University under contract No. W-7405-ENG-82.

REFERENCES

1. M. S. Good, Pacific Northwest Laboratory, private communication.
2. R. B. Thompson, T. A. Gray, J. H. Rose, V. G. Kogan, E. F. Lopes, Journal of Acoustical Society of America, Vol. 82, 1818 (1987).
3. B. P. Newberry, R. B. Thompson, E. F. Lopes, Review of Progress in Quantitative Nondestructive Evaluation, D. O. Thompson and D. E. Chimenti, Eds., Plenum Press, New York, Vol. 6A, 1987, 639.
4. R. B. Thompson, B. P. Newberry, ibid., Vol 7A, 1988, 31.
5. B. P. Newberry and R. B. Thompson, Journal of the Acoustical Society of America, Vol. 85, 2290 (1989).
6. B. P. Newberry, A. Minachi, R. B. Thompson, Review of Progress in Quantitative Nondestructive Evaluation, D. O. Thompson and D. E. Chimenti, Plenum, New York, Vol. 8B, 1989, 2089.
7. R. B. Thompson, E. F. Lopes, ibid. Vol. 5A, 1986, 117.